CEBAF PROPOSAL COVER SHEET

This Proposal must be mailed to:

CEBAF
Scientific Director's Office
12000 Jefferson Avenue
Newport News, VA 23606

and received on or before OCTOBER 31, 1989

A. TITLE: MEASUREMENTS OF PARITY VIOLATION IN ELASTIC $\vec{e}p$ SCATTERING

B. CONTACT PERSON: R. Carlini

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C. THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

/X/ YES
/ / NO

IF YES, TITLE OF PREVIOUSLY SUBMITTED LETTER OF INTENT

PARITY VIOLATION EXPTS AT CEBAF

D. ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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By KES

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CEBAF Proposal: Measurements of Parity Violation in Elastic $\vec{e}p$ Scattering

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1 Summary

Measurements of parity violation in elastic $\vec{e}p$ scattering directly measure the couplings of the Z boson to the proton. In the standard model of electroweak interactions, these couplings are well defined in terms of the parameters of the model. When we consider the currents to be carried by the quarks, clear statements can also be made about the contributions of the various flavors of quarks to these currents.

We expect CEBAF to be an ideal laboratory for the study of $\vec{e}p$ parity violation, primarily due to its excellent beam emittance, high current, and a well controlled beam polarization that may very well exceed 50%. We have identified two specific kinematic regions that are particularly interesting. One, at $Q^2 \approx 0.1\ GeV^2$, will be mainly sensitive to contributions from flavor singlet pieces of the quark currents, assuming that matrix elements of $s-$quarks in the proton are not negligible. Another, at $Q^2 \approx 0.02\ GeV^2$, will allow us to extract a value of $sin^2\theta_W$ that is rather insensitive to uncertainties in the proton form factors. These two measurements can run concurrently since they would use the same beam and target.

We propose that, as soon as beam is available at CEBAF, we begin a series of initial measurements to determine the feasibility of these measurements. This would also, of course, include studies of the many possible sources of systematic error. These measurements would not only serve as necessary ground work for ensuing precision measurements of parity violation, but they would also provide an enormous amount of data relevant to CEBAF operation. *Specifically, we request 3 weeks of initial beam time for R&D with a partial apparatus and a solid target with the following provisions:*

- 2 weeks with 50% polarized beam and 1 week with unpolarized beam
- Rapid reversal from 1 Hz to 1 kHz under experimenter control
- $\approx 50\ \mu A$ average beam current, or highest available
- 30 ns beam chopping period

2 Introduction

The "Standard Model" of electroweak interactions, based on a simple $SU(2)_L \times U(1)_R$ gauge group with spontaneous symmetry breaking, has enjoyed enormous success [Am87]. Essentially one free parameter, the weak mixing angle $sin^2\theta_W$, predicts the structure of the weak neutral current J^Z_μ in terms of the familiar electromagnetic current J^γ_μ. In particular, we have

$$J^Z_\mu = J^3_\mu - sin^2\theta_W J^\gamma_\mu \tag{1}$$

where J^3_μ is the third component of "weak isospin" defined by the group $SU(2)_L$. Consequently, the neutral current carried by both leptons and quarks is completely specified. Even though more complex models may be more appealing for a variety of reasons, they are not needed to explain the existing body of data. The "best" value for $sin^2\theta_W$ is ≈ 0.23 [Am87].

The great success of the standard model suggests two fruitful paths for future experimentation. One is obviously to test the model in as many complementary ways as possible. This is made particularly interesting since there are recent, highly precise measurements of the Z-boson mass, M_Z [Ab89], from which, in principle, one may determine $sin^2\theta_W$ to better than $\approx$1%. One may therefore test the universal applicability of Eqn.1 by studying the weak neutral current, with comparable precision, in other systems. An example of such a measurement is the proposed LCD experiment at LAMPF [Al88a] which would extract the equivalent value of $sin^2\theta_W$ in neutrino-electron elastic scattering. As we shall discuss in detail below, parity violation in elastic $\vec{e}p$ scattering is another important example, and one in which CEBAF can make an important contribution.

A second path is to assume the validity of the standard model and use the neutral current couplings to quarks, defined by Eqn.1, to extract details of hadronic structure. In particular, the "strangeness" content of the nucleon, which has received a great deal of attention lately [Ja87,Mc89,Be89,As88,Ka88,No89,Be89b], can be measured since the weak neutral current couples to different combinations of quark matrix elements than does the electromagnetic interaction. Recent measurements and analyses [As88,Ja87] suggest that there is a significant contribution to nucleon structure from strange quarks, obviously in contradiction to the simple constituent quark model. It has been proposed [Mc89,Be89a] that elastic $\vec{e}p$ parity violation be measured at kinematics designed to extract a particular piece of the matrix element $\bar{s}\gamma_\mu s$ in the proton. Below we outline the general case and discuss the implications from experiments that would be performed at CEBAF.

Parity violation in elastic $\vec{e}p$ scattering arises because of interference between electromagnetic and weak neutral currents between the electron and the proton. Therefore, such measurements can be used to extract the matrix elements of the weak neutral currents, since the electromagnetic matrix elements are well measured via the unpolarized elastic scattering differential cross sections. However, these experiments are difficult because the asymmetries are small ($\sim Q^2 G_F/\pi\alpha\sqrt{2} \times [form\ factors] \sim 10^{-6}$) and therefore one needs both a large number of counts and excellent control over systematics to obtain precision results. CEBAF is an ideal accelerator for both of these potential obstacles. The expected beam will be much more intense than that available now and it will also have extremely small emittance. Such quantities directly bear on many of the difficult potential systematic errors.

We therefore propose two new measurements. One, with forward electron scattering angles and $Q^2 \approx 0.1\ GeV^2$, will put important constraints on the matrix element of $\bar{s}\gamma_\mu s$. The second, also with forward electron scattering angles but $Q^2 \approx 0.02\ GeV^2$, will study the validity of Eqn.1 for couplings to quarks at a new level of precision. These experiments may run concurrently, although with different apparati. Since we clearly need to gain experience with the accelerator and with the polarized electron source, we request approval to begin measurements as soon as beam is available with prototypes of our anticipated detector arrays.

3 Formalism

The equation for the asymmetry A for parity violation in elastic $\vec{e}p$ scattering has been presented by many authors [Re74,Ca78,Po87,Do88,Mc89,Be89]:

$$\begin{aligned} A &\equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \\ &= -\frac{G_F Q^2}{\pi\alpha\sqrt{2}\xi}\Big[\epsilon\ G_E^\gamma G_E^Z + \tau\ G_M^\gamma G_M^Z \\ &\qquad -\frac{1}{2}(1-4sin^2\theta_W)(1-\epsilon^2)^{1/2}\sqrt{\tau(1+\tau)}G_M^\gamma G_A^Z\Big] \end{aligned} \tag{2}$$

where

- $Q^2 = -q^2 = -(p_e - p_e')^2 > 0$
- $G_F = 1.027 \times 10^{-5}/M^2$ where M is the proton mass
- $\tau = \nu^2/(-q^2) = Q^2/4M^2$ with $\nu = P_p \cdot q/M = -q^2/2M$ for elastic scattering
- $\varepsilon^{-1} = \left[1 + 2(1+\tau)tan^2\frac{\theta}{2}\right]$ where θ is the electron scattering angle
- $\xi = \varepsilon\left(G_E^\gamma\right)^2 + \tau\left(G_M^\gamma\right)^2$

and the $G_{E,M}^{\gamma,Z}$ denote the "electric" and "magnetic" form factors for the electromagnetic and weak neutral current couplings to the proton, and G_A^Z is the axial vector form factor for the weak neutral current.

The form factors are defined in the usual way. That is, assuming that the vector currents are conserved and that there are no "second class" currents, we have the following general forms for matrix elements of some vector or axial vector current operator between proton states with four momenta P and P':

$$\langle P'|J_V^\mu|P\rangle = \bar{u}\left[F_1(q^2)\gamma^\mu + \frac{i\sigma^{\mu\nu}q^\nu}{2M}F_2(q^2)\right]u \tag{3}$$

$$\langle P'|J_A^\mu|P\rangle = \bar{u}\left[G_1(q^2)\gamma^\mu\gamma^5\right]u \tag{4}$$

where $q = P' - P = p_e - p_e'$ in elastic electron scattering. (In principle, there can be another form factor, commonly called $G_3(q^2)$, multiplying $q^\mu\gamma^5$, in Eqn. 4. However, in all the expressions that follow, it would enter only in order m_e/E and is therefore neglected.) The "Sachs" form factors G_E and G_M, and the axial form factor G_A, are then defined as follows:

$$\begin{aligned} G_E(q^2) &= F_1(q^2) - \tau F_2(q^2) \\ G_M(q^2) &= F_1(q^2) + F_2(q^2) \\ G_A(q^2) &= G_1(q^2) \end{aligned}$$

We may qualitatively understand Eqn.2 as follows. The overall factor proportional to $G_F q^2/\alpha$ comes from the product of the weak neutral current ($\sim\ g_{weak}^2/(M_Z^2 - q^2) \sim\ G_F$)

and electromagnetic ($\sim \alpha/q^2$) propogators, divided by the square of the electromagnetic propogator. The first two terms in the expression involving the form factors represent the (parity violating) interference between the axial vector electron coupling ($= \frac{1}{4}$) and the vector couplings to the proton. In that sense, those two terms are analagous to the normal elastic scattering differential cross section form factors ξ which we divide by. The third term represents the interference between the weak vector coupling of the electron ($= \frac{1}{4} - sin^2\theta_W$) and the product of vector and axial vector couplings to the proton. The only such cross term which violates parity is the product of the axial form factor (i.e. G_A^Z) and the (electromagnetic) magnetic vector form factor (i.e. G_M^γ) times the difference between densities of left- and right-handed polarized virtual photons (i.e. $(1-\epsilon^2)^{1/2}$)).

The electromagnetic form factors for the proton, G_E^γ and G_M^γ are well known on the basis of many measurements of unpolarized elastic ep scattering. The neutral current form factors, on the other hand, can in principle only be known through experiments with measure the exchange of a Z boson with the proton, in the same way γ exchange measures the electromagnetic form factors. However, in terms of the standard model, the neutral current form factors $G_{E,M}^Z$ are determined from the electromagnetic form factors using Eqn. 1 where we express the currents in terms of quantities that are eigenstates of weak isospin and electric charge. When considering the proton, we write the currents as being carried by up (u), down (d), and strange (s) quarks. It should not necessarily be surprising that strange quark degrees of freedom are needed to explain these matrix elements. Indeed, one of the first treatments of weak neutral current form factors [We72] mentioned this possibility. Since the mass of the strange quark ($m_s \sim 150\ MeV$) is of the same order as the deconfinment scale of QCD ($\Lambda \sim 150\ MeV$), one might have expected this to be the case, and in fact there is some experimental evidence that the matrix elements of $\bar{s}s$ [Ja87] and $\bar{s}\gamma^\mu\gamma^5 s$ [As88] in the proton are nonzero.

It is convenient to express both the electromagnetic and weak neutral current form factors in a notation that exploits the $SU(3)_{flavor}$ character of the quark structure. We separate each current into 0, 3, and 8 components corresponding to the diagonal 3×3 matrices λ^0, λ^3, and λ^8 [Be89]. Realizing that the weak isospin of the u quark is $+\frac{1}{2}$, and that for the d and s quarks it is $-\frac{1}{2}$, and also that the current J_μ^3 of Eqn. 1 is only carried by left handed quarks (e.g. $\frac{1}{2}(1-\gamma^5)u$), we arrive at the following expressions for the currents [Be89]:

$$J_\mu^\gamma = \sum_{\alpha=0,3,8} a^\alpha J_{\mu V}^\alpha \tag{5}$$

$$J_\mu^Z = \sum_{\alpha=0,3,8} \left[\left(b^\alpha - a^\alpha sin^2\theta_W \right) J^\alpha_{\mu_V} - b^\alpha J^\alpha_{\mu_A} \right] \tag{6}$$

where

$$\begin{array}{lll} a^0 = 0 & a^3 = 1 & a^8 = \frac{1}{\sqrt{3}} \\ b^0 = -\frac{1}{4} & b^3 = \frac{1}{2} & b^8 = \frac{1}{2\sqrt{3}} \end{array}$$

and $J^\alpha_{\mu_V} = \bar{\psi}\lambda^\alpha\gamma_\mu\psi$ and $J^\alpha_{\mu_A} = \bar{\psi}\lambda^\alpha\gamma_\mu\gamma_5\psi$ where ψ is a column vector of u, d, and s. We associate the current $J^0_{\mu_V}$ with the baryon number, $J^3_{\mu_V}$ with the isospin, and that *if the* $\bar{s}s$ *matrix elements are zero then* $J^0_\mu = \frac{2}{\sqrt{3}}J^8_\mu$. In the limit of strong isospin symmetry, the 0 and 8 components are the same for protons and neutrons (i.e. give the same contributions for u and d quarks), while the 3 components change sign.

The 0, 3, and 8 components of the form factors follow from the definitions of the currents. In many cases [Ka88,Mc89,Be89] the values of the form factors at $q^2 = 0$ are known from the proton and neutron charges and magnetic moments, and from neutron and hyperon beta decay. In particular, we have

$$\begin{array}{lll} G_E^0(0) = 1 & G_E^3(0) = \frac{1}{2} & G_E^8(0) = \frac{\sqrt{3}}{2} \\ & G_M^3(0) = \frac{1}{2}(\mu_p - \mu_n) & G_M^8(0) = \frac{\sqrt{3}}{2}(\mu_p + \mu_n) \\ & G_1^3(0) = |g_A/g_V| = F + D & G_1^8(0) = \frac{1}{\sqrt{3}}(3F - D) \end{array}$$

Here $\mu_p = 2.79$ is the proton magnetic moment and $\mu_n = -1.91$ is the neutron magnetic moment. Also, $|g_A/g_V| = 1.262$ [Kl88] and in the limit of no strange quark contributions, we have $G_A^Z(0) = -\frac{1}{2}G_1^3(0) = -1.262/2$. The values of $G_M^0(0)$ and $G_1^0(0)$ need to be determined in other experiments. Since these singlet form factors are part of the weak neutral current, but not the electromagnetic current, (i.e. $a^0 = 0$ in Eqn. 5) we need studies of weak neutral current processes if we are to fill out this picture [Ka88].

It is convenient to assume strong isospin and write the neutral current vector form factors in terms of the electromagnetic form factors of the proton and neutron. In that case, we have ($G_{E_p} \equiv G_E^\gamma$)

$$G_E^Z(q^2) = \left(\frac{1}{4} - sin^2\theta_W\right) G_{E_p}(q^2) - \frac{1}{4}G_{E_n}(q^2) - \frac{1}{4}G_E^s(q^2) \tag{7}$$

$$G_M^Z(q^2) \;=\; \left(\frac{1}{4} - sin^2\theta_W\right) G_{M_p}(q^2) - \frac{1}{4}G_{M_n}(q^2) - \frac{1}{4}G_M^s(q^2) \tag{8}$$

where

$$G_{E,M}^s(q^2) \equiv G_{E,M}^0(q^2) - \frac{2}{\sqrt{3}}G_{E,M}^8(q^2) \tag{9}$$

(We implictly assume that the strange quark matrix elements are the same in the proton or neutron, that is, they are pure isoscalar.) The form factors $G_{E,M}^s(q^2)$ measure the "strangeness" contributions to the nucleon's electric charge and magnetic moment distributions, respectively. In that sense, $G_E^s(0) = 0$ while $G_M^s(0)$ is undetermined. An interesting proposal was made, based on Eqn. 2 and Eqn. 7, that parity violating $\vec{e}p$ scattering be used to determine the electric form factor of the neutron, G_{E_n} [Do88]. However, in light of the possibility that both G_E^s and G_M^s are nonzero, they must be determined independently before this is tractable [Be89]. On the other hand, it is clear that independent measurements of G_{E_n} and G_{M_n} may be used to help determine the weak neutral current form factors at finite q^2.

Modifications to this picture are numerous, involving electroweak radiative corrections [Dm89], odd parity components of the proton wave function [Ha89], and modifications to the standard model [Ly87,Ge89]. Each of these must be investigated further to understand their impact on our proposed measurements, especially in light of recent precise measurements of M_Z. An example of a modification to the standard model which may be revealed rather uniquely through elastic $\vec{e}p$ scattering is shows in Fig. 3. In this case, the standard model gauge group is imbedded in an $E(6)$ gauge group which is spontanteously broken down to the present standard model [Ly87]. A new weak neutral current appears and the mass of the new intermediate boson ($M_{Z'}$) would be constrained sensitively through measurements of $\vec{e}p$ parity violation as demonstrated in Fig. 3 [Ly87a]. This example emphasizes the need to test the standard model in several complementary ways.

4 Kinematic Regions and Sensitivities

Now we examine in some detail the behavior of Eqn. 2 in three specific kinematic regions, namely $Q^2 = 0.1\ GeV^2$ and $\varepsilon \to 0$ (i.e. backward scattering), $Q^2 = 0.1\ GeV^2$ and $\varepsilon \to 1$ (i.e. forward scattering), and $Q^2 = 0.02\ GeV^2$ and $\varepsilon \to 1$. We shall show that the

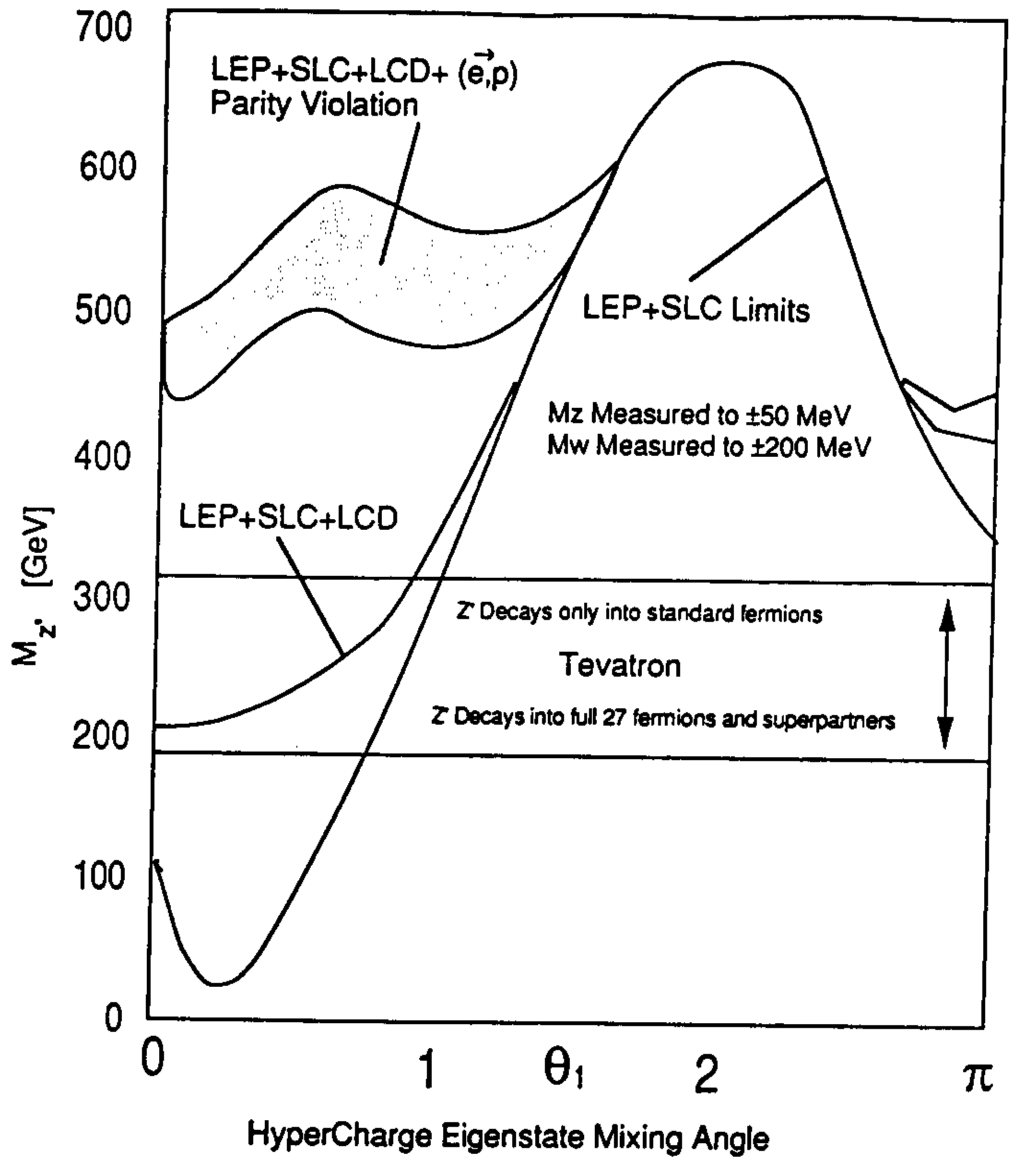

Figure 1: Parity violation in elastic $\vec{e}p$ scattering puts sensitive limits on the mass of a new boson carrying a new weak neutral current. This new current would be implied by a unified $E(6)$ model of the fundamental interactions.

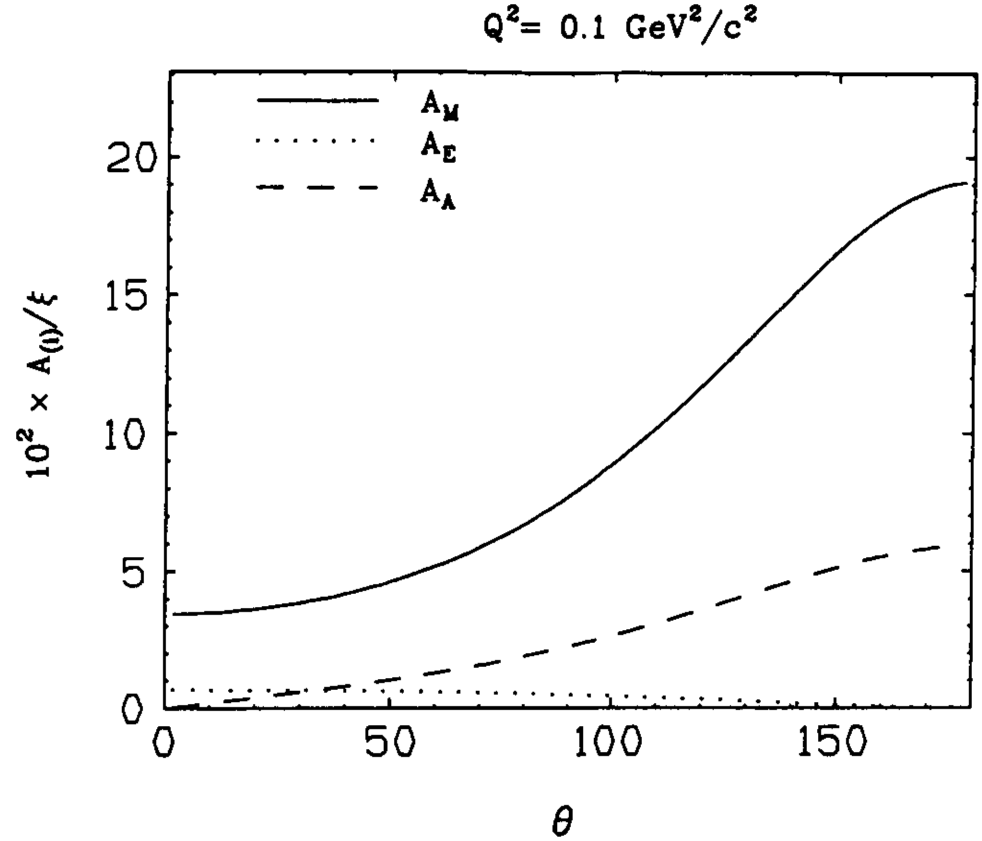

Figure 2: Contributions to the asymmetry in Eqn. 2 from the form factor dependent terms as a function of electron scattering angle θ for $Q^2 = 0.1\ GeV^2$. An overall factor of $G_F Q^2/\pi\alpha\sqrt{2}$ has been omitted. These kinematics would be particularly sensitive to strange quark contributions to the proton form factors should they exist.

first two of these constrain the strange quark form factors G_E^s and G_M^s to a reasonable range. The third region is most sensitive to electroweak effects and the equivalent value of $sin^2\theta_W$. The first region is the subject of an active proposal at the MIT-Bates Linear Accelerator Center [Be89a] while the second and third are the focus of this proposal.

Figure 2 shows the relative contributions to the asymmetry from the "electric" (A_E), "magnetic" (A_M) and "axial" (A_A) terms in Eqn. 2 where we determine the weak neutral current form factors from Eqns. 7 and 8 assuming that $G_E^s = G_M^s = 0$ and a standard representation for G_{E_n} [Ga71]. We now discuss the regions near $\theta = 180°$ and $\theta = 0°$ in more detail.

Backward Scattering at $Q^2 \approx 0.1\ GeV^2$. For backward scattered electrons, the longitudinal polarization ϵ vanishes and consequently there is no contribution to Eqn. 2 from electric form factors. It has been proposed to determine the $q^2 = 0$ value of the singlet form factor G_M^0 (and consequently G_M^s) in this manner [Mc89,Be89a] to $\approx 10\%$.

In this limit, Eqn. 2 becomes

$$A(\epsilon \to 0) = -\frac{G_F Q^2}{\pi\alpha\sqrt{2}}\left[\frac{G_M^Z}{G_M^\gamma} - \frac{1}{2}(1 - 4sin^2\theta_W)\sqrt{\frac{1+\tau}{\tau}}\frac{G_A^Z}{G_M^\gamma}\right] \tag{10}$$

Note that the contribution from the (poorly known) axial vector form factor grows without bound as $q^2 \to 0$, although it is suppressed by the factor $(1 - 4sin^2\theta_W)$ since $sin^2\theta_W \sim \frac{1}{4}$. At $Q^2 = 0.1\ GeV^2$ the contribution from the axial term is $\approx 10 - 30\%$, depending on radiative corrections. If we assume that that the uncertainty in G_A^Z is on the order of 20% (see for example [Ah87]), then it would contribute a few percent error to the determination of G_M^Z. Note, however, that we must assume that the form factors evaluated at $Q^2 = 0.1\ GeV^2$ are still given by their values at $q^2 = 0$, or at least their q^2 dependences are all the same and therefore cancel.

Forward Scattering at $Q^2 \approx 0.1\ GeV^2$. In this limit, $\epsilon \to 1$ and there is no axial vector form factor contribution. As opposed to the backward scattering region, however, there *is* a contribution from the electric form factors. In particular, we find that Eqn. 2 becomes

$$A(\epsilon \to 1) = -\frac{G_F Q^2}{\pi\alpha\sqrt{2}}\left[\frac{G_E^\gamma G_E^Z + \tau G_M^\gamma G_M^Z}{(G_E^\gamma)^2 + \tau\,(G_M^\gamma)^2}\right] \tag{11}$$

Consequently, such a measurement would extract G_M^0 in the same manner as a measurement at backward angles, except that we have traded sensitivity on G_A^Z for sensitivity to the electric form factors. Given such a measurement at backward angles, however, and assuming that the contributions from G_A^Z are understood to a sufficient level, we would use existing data for the proton [Wa89] and anticipated data for the neutron [Mi88] electric form factors to constrain $G_E^s(Q^2 \approx 0.1\ GeV^2)$. At $Q^2 = 0.1\ GeV^2$, one finds that $\sim 10\%$ measurements of the asymmetry at both forward and backward angles are complementary, and these measurements would imply an error in $G_E^s \sim 0.02$. We do not know a priori what G_E^s should be, but if we follow the example of G_{E_n} (which analogously measures the charge distribution for the neutron), we find that $G_{E_n} \approx \tau G_{M_n}$. With $G_M^s \sim \pm 1$, we then expect $G_E^s \sim \pm\tau = \pm 0.03$. Hence, these measurements would constrain G_E^s to at least its "natural" limits.

In principle, we could use these kinematics to determine $sin^2\theta_W$ to $\approx 1\%$ assuming that we knew the relevant proton form factors to enough precision from other experiments. The sensitivity to $sin^2\theta_W$ comes primarily from the factor $(1 - 4sin^2\theta_W)$

multiplying the proton electromagnetic form factors in Eqns. 7, 8. In order to measure $(1-4sin^2\theta_W)$ to $\approx$ 10% (and so $sin^2\theta_W$ to $\approx$ 1%) at practical kinematics ($E_{beam} \approx 4\ GeV$), we would need new measurements of G_{M_n} and G_{E_n} to precisions of $\sim$ 3% and $\sim$ 15% respectively (i.e. 2 to 3 times better than they are presently known), and independent knowledge of the strange form factor G_M^s to $\sim 5\% \times \pm 1$. In addition, we must make assumptions about the Q^2 behavior of the form factors. It would then appear that our sensitivity to $G_E^s(Q^2 = 0.1\ GeV^2)$ would overshadow a precision measurement of $sin^2\theta_W$. On the other hand, if precise measurements of the neutron form factors are completed (which we *do* expect to happen), and other measurements and theoretical analyses put strong constraints on strange matrix elements, then this would be a suitable way to extract $sin^2\theta_W$. Indeed, if the measurement results in a value consistent with no strange quark effects and the standard model prediction fo $sin^2\theta_W$, then a significant constraint on both will be obtained.

Forward Scattering at $Q^2 \to 0$. In the limit $Q^2 \to 0$, the contributions to Eqn. 2 from both magnetic and axial terms vanishes. In addition, we know the values of the electric form factors at $Q^2 = 0$, in particular $G_{E_p}(Q^2 = 0) = 1$ and $G_{E_n}(Q^2 = 0) = G_E^s(Q^2 = 0) = 0$. Therefore, Eqn. 2 reduces to the following form:

$$A(Q^2 \to 0) = -\frac{G_F Q^2}{4\pi\alpha\sqrt{2}}\left(1 - 4sin^2\theta_W\right) \tag{12}$$

and consequently a $\approx$ 10% measurement of this asymmetry would yield a $\approx$ 1% value for $sin^2\theta_W$ in the important regime of $Z - quark$ coupling, rather independent of proton structure.

Unfortunately, however, the asymmetry itself vanishes as $Q^2 \to 0$ and some finite value of Q^2 must be chosen so that the uncertainty is measureable. Basically, this requires $\tau \ll (\frac{1}{4} - sin^2\theta_W) \approx 0.02$. We choose $Q^2 = 0.02\ GeV^2$ ($\tau = 0.006$) which gives $A = 1.7 \times 10^{-7}$. Given an electron beam polarization $\sim$ 50%, this means that our experiment must ultimately measure an asymmetry with precision of $\sim 10^{-8}$. Systematic error has been reduced to this level in previous experiments in $\vec{p}p$ scattering parity violation [Yu86], so it may be possible to do this well at CEBAF given the superior beam characteristics.

The relative contributions to Eqn. 2 at $Q^2 = 0.02\ GeV^2$ and forward angles is shown in Fig. 3. Although the electric contribution dominates, there is a sizable contribution from the magnetic terms. Also, the electric term is not purely from G_{E_p} but has contamination from G_{E_n} and G_E^s. However, even current knowledge of the proton and neutron

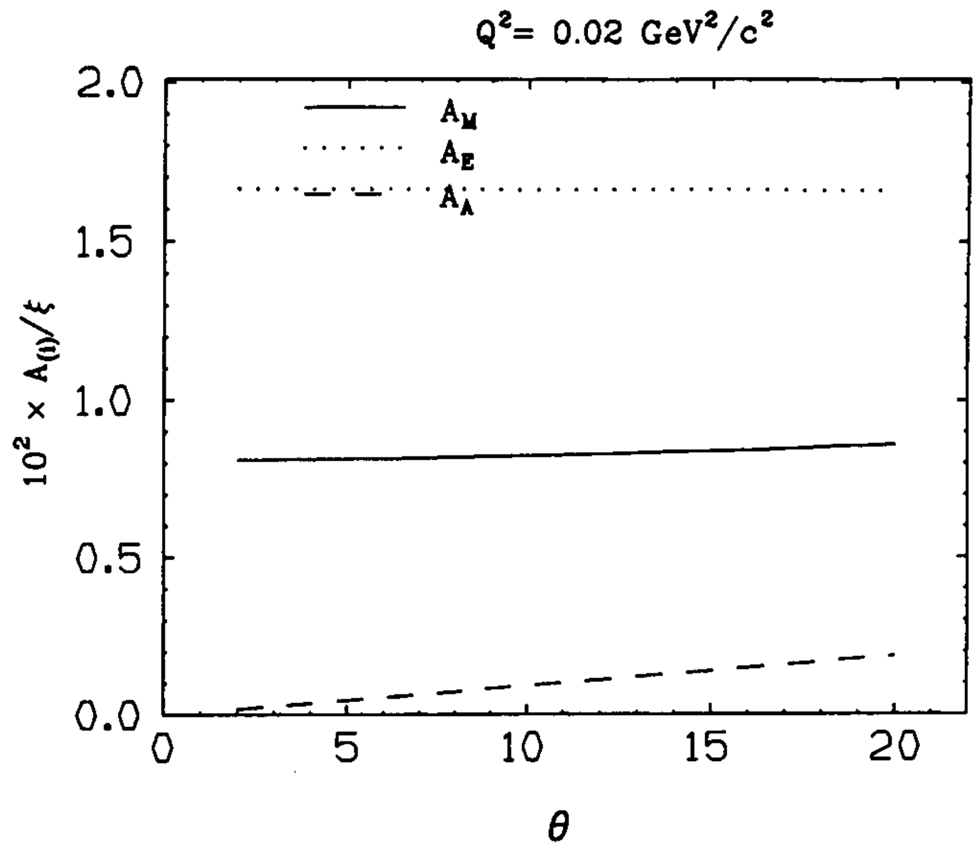

Figure 3: Contributions to the asymmetry in Eqn. 2 from the form factor dependent terms as a function of electron scattering angle θ for $Q^2 = 0.02\ GeV^2$. An overall factor of $G_F Q^2/\pi\alpha\sqrt{2}$ has been omitted. These kinematics are the basis for measurements of $sin^2\theta_W$ in elastic $\vec{e}p$ scattering.

form factors is sufficient to reduce the undertainty in their contribution to a negligible level. Also, if $G_M^s \sim \pm 1$ is measured to $\approx 20\%$, either at Bates or CEBAF (but preferably both), then its contribution to the uncertainty is well within the goal of 10% in the asymmetry.

5 Proposed Measurements at CEBAF

Execution of these measurements will require high currents ($\sim 100\ \mu A$) on relatively thick cryogenic targets ($\sim 15\ cm\ LH_2$); good beam quality including emittance and halos; high electron beam polarization with good control over transverse components; rather specialized experimental equipment; and significant amounts of running time. For all of these reasons, we do not expect to begin data taking for final results until some time after CEBAF has been operating. *However,in order to prepare for final data taking,* *it is imperative that we begin as soon as beam is available to understand details of the accelerator and our experimental apparatus. We therefore propose that we have initial beam time to carry out these first measurements using prototypes of our anticipated final detector arrays.* It seems clear to us that *Hall C* is the correct end station to pursue these rather specialized, high luminosity measurements.

The design of the experimental apparatus is, at this time, still in a conceptual state. However, we do not expect a specialized experiment for measuring $\vec{e}p$ elastic parity violation to be very intricate, and could be constructed in roughly 2-3 years time. Below we sketch our current ideas about how we would make these measurements, including estimates of potential background rates. We also point out that when the time scale for completion of the STAR spectrometer [Al88] is clearer, we may direct our attention to using that device for these measurements.

One crucial aspect of these measurements is development of high power cryogenic targets ($\sim 500\ W$). Such targets will be part of CEBAF's initial operation, and a similar target, specifically designed to be used in a parity violation experiment, is being developed [Be89a]. Another important development will be implementation of an electron beam polarimeter. We are currently investigating a variety of possible options.

We are proposing two measurements, one at $Q^2 = 0.1\ GeV^2$ and the other at $Q^2 = 0.02\ GeV^2$, both at forward angles where $\epsilon \to 1$. These kinematic regions can simultaneously be reached with a beam energy $E = 2\ GeV$, at scattering angles of $\theta \approx 10°$ and $\theta \approx 4°$ respectively. Consequently, both measurements can be run with the same beam and target, but with different detection equipment. If we detect only the scattered electron, however, we must be careful not to accept inelastically scattered electrons into our apparatus. Figure 4 shows the differential cross section for inclusive electron scattering from protons for kinematics corresponding to $Q^2 = 0.1\ GeV^2$ and $Q^2 = 0.02\ GeV^2$, calculated according to a well known parameterization [Br76]. If our electron detector integrated over effectively all electron energies (e.g. as would happen with a threshold Cerenkov counter), then a significant amount of inelastic background would be counted as well. Since we aim for a $\approx 10\%$ measurement at $Q^2 = 0.02\ GeV^2$, and the integrated inelastic cross section is less than 10% of the elastic cross section *and* well understood, a simple apparatus should suffice for this measurement. However, this is not the case for the measurement at $Q^2 = 0.1\ GeV^2$, and some other detection scheme must be devised.

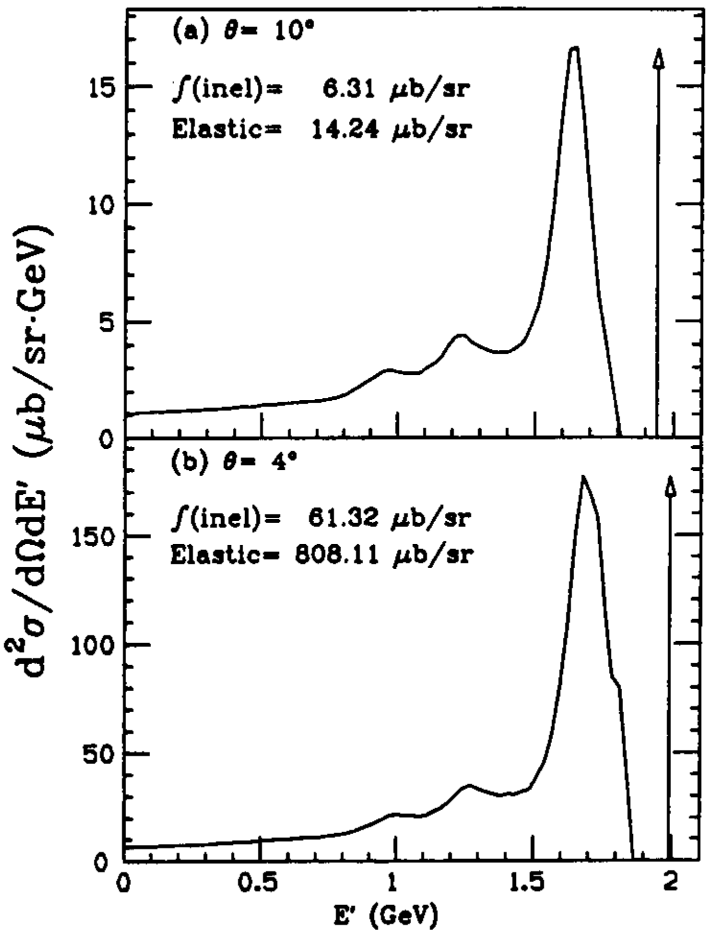

Figure 4: Calculated inelastic and elastic scattering cross sections at the angles corresponding to elastic scattering at $Q^2 = 0.1\ GeV^2$ and $Q^2 = 0.02\ GeV^2$ for a fixed beam energy $E = 2\ GeV$. The arrow indicates the position of the elastic peak.

5.1 A Measurement at $Q^2 = 0.1\ GeV^2$

It is our current thinking that it should be possible to carry out this measurement by detecting the elastically scattered protons instead of the electrons. The scattered electrons are contaminated at the 50% level by inelastic processes, the majority being from excitation of the $\Delta(1232)$ and so have reasonably high energy (see Fig. 4). In the absence of some sort of magnetic separation (that may be possible in later experiments with the STAR [Al88]), electron detection, even in coincidence with protons, will not serve much useful purpose. Proton background from this process, on the other hand, would emerge over a much larger angular range and with significantly less energy than elastically scattered protons. Initial estimates using the Monte Carlo program CELEG [Jo89] tend to confirm this expectation.

We would detect protons over an approximate angular range $65° \leq \theta_p \leq 80°$ and determine their Q^2 on the basis of Time-of- Flight (TOF) measurements. We would run the accelerator in a mode where full average beam current is maintained, but polarized electrons are injected in pulses separated by $\approx 30\ ns$. With an array of proton counters located at a distance of $2\ m$ from the target, flight times for the protons of interest are between roughly $15\ ns$ and $25\ ns$. Since, for elastic scattering, the proton energy is simply proportional to Q^2, we measure Q^2 to sufficient precision by determining TOF to $\approx 300\ ps$. The beam pulse width is completely negligible on this scale, and with scintillation counters can achieve this timing with currently available scintillators and photomultiplier tubes.

An important consideration is whether or not the proton counters can sit in an open environment looking essentially unobstructed at the target. We have used the measurements of the CEBAF LAS collaboration of low energy backgrounds due to electron beams [Me89]. Scaling up to our expected luminosity, we find that if we shield the scintillators from the target by $\sim \frac{1}{2}\ gm/cm^2$ of some low Z material (such as Carbon sheets), then the soft electrons and very low energy gamma rays are eliminated, and negligibly effect the protons we need to detect. The remaining flux of gamma rays is for energies above $\sim 100\ keV$ and would represent approximately $10^4/pulse$ into our solid angle. This would be compared to an elastic scatter rate of $\approx 4/pulse$. The protons would, however, give signals greater than $4\times$ (minimum ionizing), or nearly $1\ MeV$ in reasonable thickness counters. The gamma rays, on the other hand, would only have a few % probability of interacting in the counters, and even then they would only deposit some fraction of their energy. Therefore, we believe that we may be able to withstand this background, especially since it arrives far earlier than the proton signals. *Understanding this background will be an important result of our initial R&D measurements.* Another option we are investigating is the use of large permanent magnets to bend the protons out of direct view of the target before being detected.

Taking data in this way implies that we actually count events as opposed to integrating the flux over the time of the beam pulse. This means that dead time effects are of crucial importance, as well as the ability to take data at extremely high rates. We anticipate a data acquisition system that would have independent processors working on individual parts of the proton detection array, histogramming, among other things, the TOF measurements from the individual counters.

Assuming an electron beam polarization of 50%, and a 100 μA beam current on a 15 cm LH_2 target (i.e. $\mathcal{L}$=4 $\times$ 10^{38} $cm^{-2}sec^{-1}$), we would achieve a statistical precision $\sim 10^{-7}$ with less than 1 month of beam on target. Certainly, important strides can be made with much shorter running periods with the intent of understanding systematics uncertainties.

5.2 A Measurement at $Q^2 = 0.02\ GeV^2$

Using the same target and 2 GeV beam as for the above measurement, we would investigate the possibility of measuring the asymmetry at forward angles and very low Q^2. As we show above, at $Q^2 = 0.02\ GeV^2$, the asymmetry (albeit small), is rather insensitive to uncertainties in the hadronic structure and would more directly measure $sin^2\theta_W$. At this time, we anticipate carrying out this measurement using threshold gas Cerenkov counters arranged azimuthally and at very small angles ($\theta \approx 4^\circ$) to the beam direction. Although 4° is many standard deviations away from the beam in terms of multiple scattering and bremsstrahlung radiation from the target, the rather long tails of these distributions will be more difficult to deal with. However, they can be simulated rather straightforwardly using standard Monte Carlo programs. We recognize that the Cerenkov counter must have a very low mass support structure and the region along the beam filled with a low Z gas, probably hydrogen or helium. The running time required to achieve the desired precision would be roughly 3000 hours.

5.3 Experimental Layout

With the above ideas in mind, we have sketched a diagram of our anticipated experimental apparatus in Fig. 5. The $Q^2 = 0.1\ GeV^2$ measurement would be made using the proton scintillation counter arrays. Note that the proton counters are in separate ϕ-symmetric modules, each with several scintillation detectors segmented in the direction of θ_p. A flight path of $\approx 2\ m$ from the target to these detectors will give sufficient energy (and therefore Q^2) resolution via TOF. Thin low-Z sheets in front of the proton counters should provide sufficient shielding from very low energy (i.e. keV) gamma rays. The counters are relatively insensitive to high energy gamma rays. The count rate from elastic $\vec{e}p$ scattering would be $\approx 4/pulse$ or $1 - 2 \times 10^8/sec$, integrated over all proton counters. A special purpose data acquisition system, probably based on a simple parallel network of fast processors and memory, will be needed.

The small angle Cerenkov counters are designed to be sensitive to elastic scattering in the range of $Q^2 = 0.02\ GeV^2$. An important issue is the condition of the beam halo after passing through the target chamber, but we attempt to minimize the interaction of this halo by surrounding the region with an atmosphere of some low Z gas. These counters would run at an extremely high rate and conventional flux counting techniques will be used to extract the asymmetry.

5.4 Running Time

Such experiments need to be run in stages, building on the experience of one run to prepare for the next. Following is an example of the sequence of running times we will request to carry out these measurements:

Prototype Tests (*This Proposal*). We request three weeks of beam time to study backgrounds, polarized source behavior, and to get a first estimate of the magnitudes of the systematic errors. All such runs would use prototype detector arrays and a solid target, probably ^{12}C.

Detector Shakedown. After the detector systems are more of less complete, we would request $\approx 1\ month$ of beam time to study the integrated detector and data acquisition system. We expect that this would also be done with a solid target.

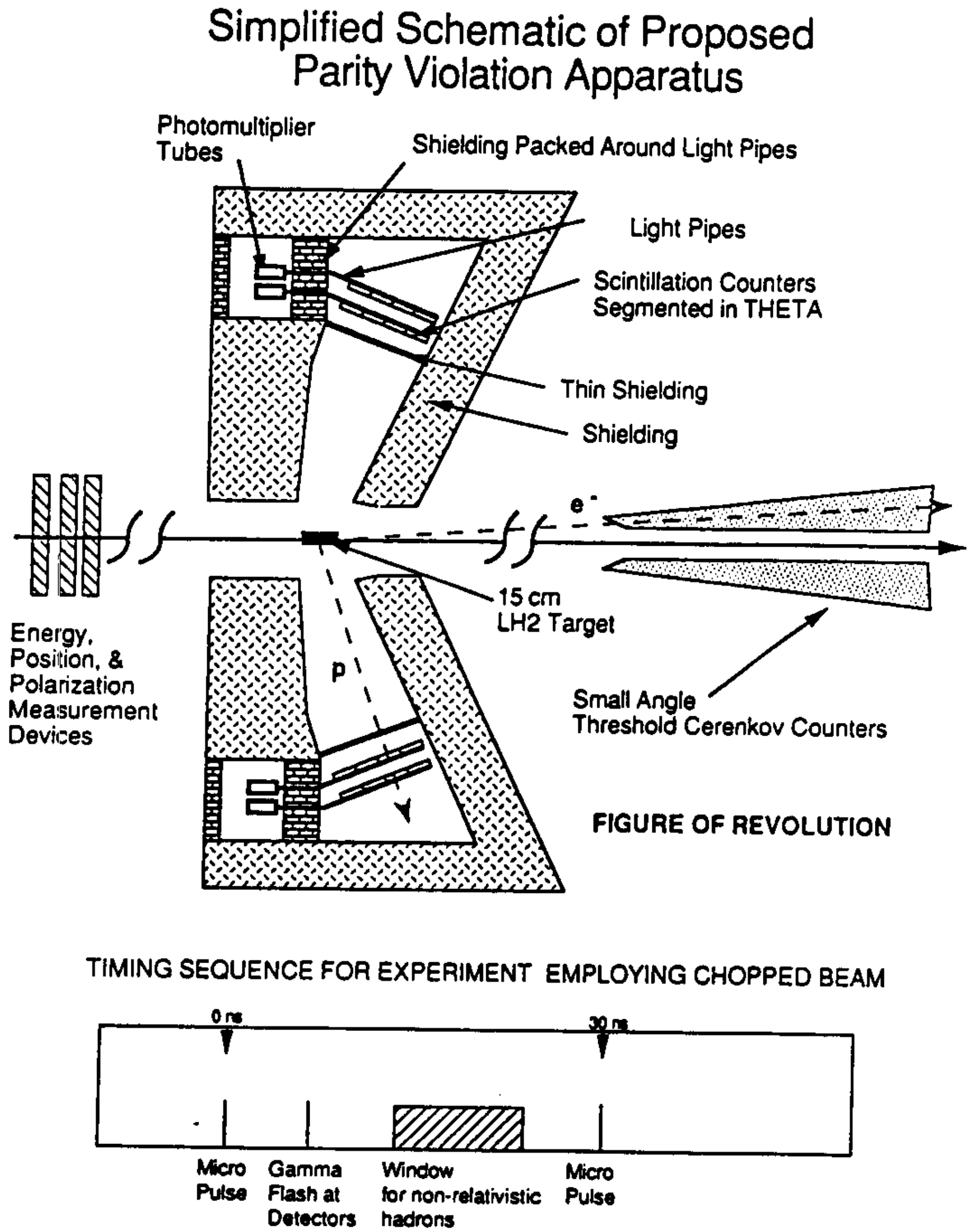

Figure 5: Our present concept of an experimental arrangement for simulataneous measurements of the parity violation asymmetry at both $Q^2 = 0.1\ GeV^2$ and $Q^2 = 0.02\ GeV^2$.

Continued Shakedown with Cryogenic Target. When the LH_2 target is ready, we would once again request ≈ 1 *month* of beam to understand systematics with the LH_2 target, and hopefully acquire some data suitable for preliminary results.

Production Running. At this point we would request ≈ 2 *months* of beam time to acquire enough data to measure $A(Q^2 = 0.1\ GeV^2)$ to $\approx 10\%$ or better. This would yield a measurement of, or a limit on, the strange matrix elements G_M^s and possibly G_E^s. If results at this point are consistent both with the standard model and with no strange quark contributions, then important new limits would be placed on each. Data acquired from the low angle detectors would yield a measurement of $sin^2\theta_W$ to new precision in the "lepton-quark" sector independent of the outcome of the extracted values of $G_{E,M}^s$. Further data taking would certainly depend strongly on results at this time.

6 Control of Systematic Errors at CEBAF

Any characteristics of the electron beam that change when the helicity is reversed may affect the scattering measurement and give rise to a spurious asymmetry that mimics parity nonconservation. It is therefore necessary to monitor the beam energy, polarization, position, intensity, and size. Each of these beam properties must be monitored continuously, and, if necessary controlled to a level sufficient to ensure that they make an insignificant contribution to the overall uncertainty relative to the level of the statistical precision of the measurement. The spurious contributions to a parity violation experiment can be parameterized as follows:

$$A_m = A + \Delta E\frac{\partial A}{\partial E} + \Delta P\frac{\partial A}{\partial P} + \Delta r\frac{\partial A}{\partial r} + \Delta I\frac{\partial A}{\partial I} + \Delta f\frac{\partial A}{\partial f} + \cdots \qquad (13)$$

where A_m is the measured asymmetry and A is the actual asymmetry. ΔE, ΔP, Δr, ΔI, and Δf are the magnitude of helicity correlated energy, polarization, position, intensity, and phase space (beam size) variations carried by the beam, respectively. The partial derivatives $\partial A/\partial E$, etc. define the detector's sensitivity to the corresponding property of the beam. The goal, therefore, is to minimize all variations in the beam's properties and the detector's sensitivity to each component.

For example, the term Δr is expected to be very small in the CEBAF experiment since its magnitude is primarily determined by the beam diameter, and parity experiments have been conducted, at LAMPF, SIN, and Bates, using beam diameters 10 to 100 times larger than anticipated for CEBAF. The relative size of the corresponding sensitivity term, $\partial A/\partial r$, is determined primarily by the inverse of the size of the detector times the magnitude of beam motion on the target. Again, previous experiments have employed smaller and less sophisticated apparatus, and have successfully dealt with very jittery beams. Thus, we expect the $\Delta r \cdot \partial A/\partial r$ term to be very small in this third generation parity experiment. Owing to the quality of the detector being proposed and the extremely high quality expected for the CEBAF beam, similar results are anticipated for the other terms. Note, also, that only the helicity correlated components of the above expression contribute to systematic uncertainties.

A continuous precision measurement of the beam energy and a servo system to apply a correction signal to the klystrons supplying power to the rf cavities may be required. It may also be necessary to monitor and control beam intensity variations and apply a correction signal to the source. Control systems for beam motion and phase space (size) modulation may be required, but residual transverse polarization is not expected to be a problem at CEBAF. Generally, such systems exist within accelerators, but parity experiments usually require greater accuracies than equipment designed to serve solely as accelerator diagnostics. Fortunately, high beam quality and large apertures are intrinsic to superconducting linacs. Thus, little or no beam halo and stable operation are anticipated. In order to take maximum advantage of these features the collaboration intends to interact closely with the CEBAF accelerator division, at an early stage, to minimize the need to work around subtle, unanticipated machine characteristics, as has been the case for previous experiments.

7 Possible Subsequent Measurements

It is possible to directly isolate $sin^2\theta_W$ and the strange quark form factor G_E^s by measuring elastic scattering parity violation on a pure isoscalar target, assuming that G_E^s is the same for free nucleons as for nucleons in nuclei. In particular, for elastic scattering from a pure isoscalar, $J^\pi = 0^+$ target we have the expression [Be89,Du89]

$$A(0^+) = \frac{G_F Q^2}{\pi\alpha\sqrt{2}}\left[sin^2\theta_W + \left(\frac{A}{4Z}\right)\frac{G_E^s}{G_{E_p}}\right] \tag{14}$$

Since $G_E^s(Q^2 = 0)$=0, measurements (possibly simultaneous) of this asymmetry at two or more values of Q^2 would allow an extrapolation to $Q^2 = 0$, extracting both $sin^2\theta_W$ and $G_E^s(Q^2)$. (Note that results at $Q^2 = 2.3 \times 10^{-2}\ GeV^2$ on ^{12}C will soon be available [Mi88a].) An important consideration for such a measurement is the level to which the ground state of the target nucleus is pure isoscalar. Calculations indicate that admixtures should be particularly small for ^4He [Do89]. This choice is attractive for experimental considerations because the energy of the first excited state is very large ($\approx 20\ MeV$) and the form factors are known over a large range of Q^2 [Fr67,Fr68].

With even crude resolution on the scattered electron energy, it would be possible to measure parity violating *inelastic* scattering to the $\Delta(1232)$ resonance (see Fig. 4) and study aspects of its structure and possibly test the standard model in other ways [Ca78]. With moderate momentum resolution ($\sim 10^{-3}$), it would be possible to examine novel aspects of nuclear structure via inelastic scattering to excited states of complex nuclei, for example ^{12}C [Wa77,Se79].

Each of these possible measurements would require that we detect the scattered electron with moderate energy resolution, requiring some sort of magnetic spectrometer. A very suitable instrument for these measurements would be the STAR spectrometer [Al88], an azimuthally symmetric cluster of 8 focussing spectrometers. Figure 7 shows a schematic of a possible experimental setup. Rays are traced through the magnetic field, corresponding to elastic scattering from ^4He and for inelastic scattering at the threshold for π production. Integrating electron detectors would then be placed at the appropriate focal point. The large solid angle and azimuthal asymmetry are obvious large advantages for these measurements.

We therefore also propose that we use the STAR spectrometer, as soon as both it and beam are available, to study its use in such parity violation experiments. This would include possible use in either or both of the two primary kinematic regions we have identified for $\vec{e}p$ elastic scattering parity violation.

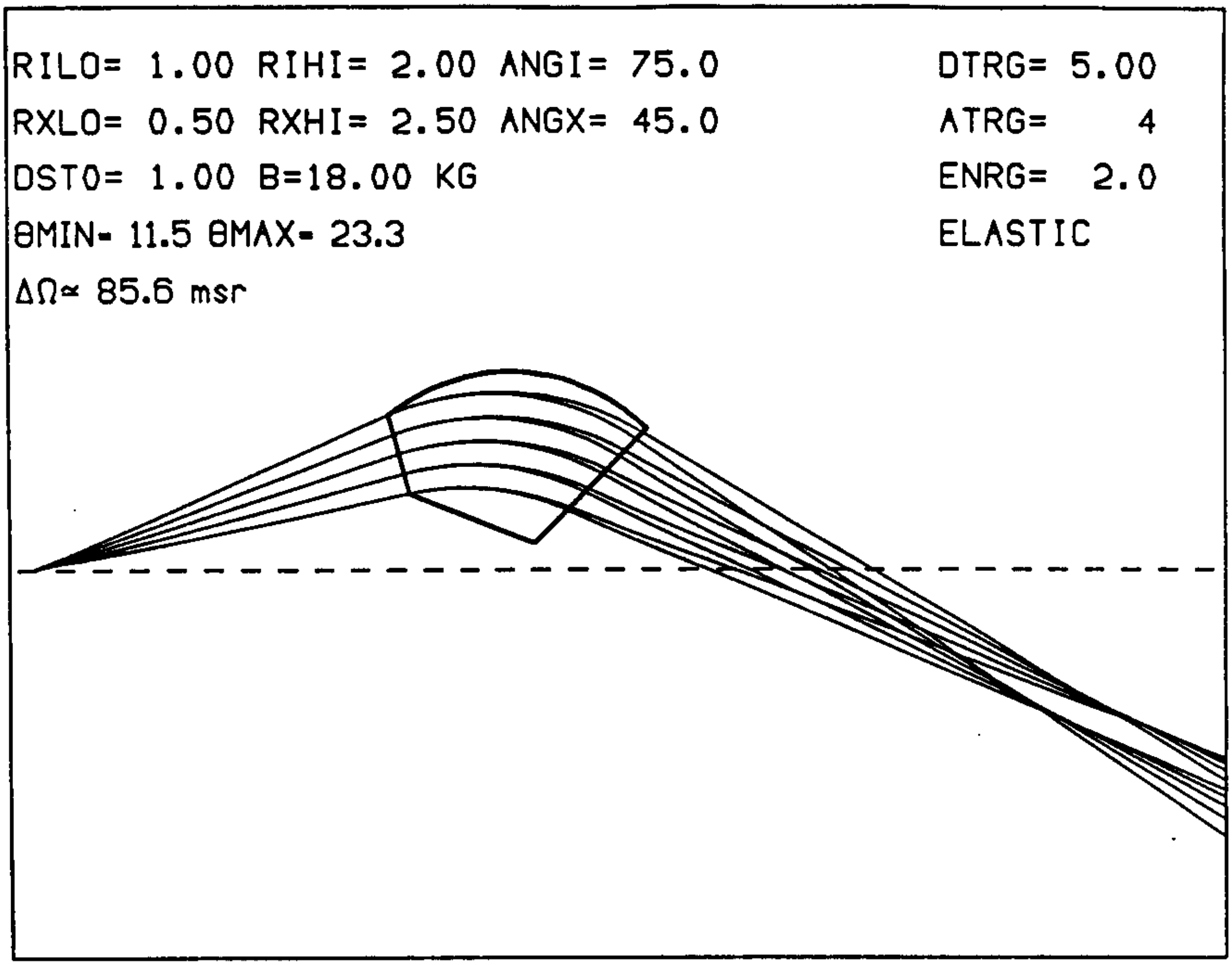

Figure 6: In order to measure parity violation in electron scattering processes that require good resolution in scattered electron energy, one would use the STAR spectrometer. This figure shows approximate rays traced through one section of the STAR. The rays correspond to elastic scattering from ^4He and for inelastic scattering at the threshold for π production.

8 Conclusion

Parity violation in elastic $\vec{e}p$ scattering can reveal novel aspects of nucleon structure and provide important new information for testing the standard model of electroweak interactions. We have shown that specific kinematic regions can be used to enhance or suppress possible contributions from strange quark degrees of freedom. We have studied specialized experimental equipment that we believe may prove to be suitable for measurements in these two kinematic regions. We propose that, as soon as beam is available, we test prototype arrangements of this equipment.

When the STAR spectrometer is available, a variety of new experiments may be possible, and we would request beam time at that point to study those possibilities.

References

[Ab89] G.S. Abrams, et.al., Phys. Rev. Lett. **63** (1989) 724

[Ah87] L.A. Ahrens, et.al., Phys. Rev. D **35** (1987) 785

[Al88] R.Alarcon, et.al. CEBAF Letter of Intent 88-74, Unpublished

[Al88a] R.C.Allen, et.al. Los Alamos Proposal LA-11300-P (1988)

[Am87] Ugo Amaldi, et.al. Phys. Rev. D **36** (1987) 1385

[As88] Ashman, et.al., Phys. Lett. B **206** (1988) 364

[Be89] D.H.Beck, Phys. Rev. D **39** (1989) 3248

[Be89a] D.Beck, et.al. Letter of Intent submitted to Bates Linear Accelerator Program Advisory Committee, April 1989

[Be89b] V.Bernard and U.Meissner, Phys. Lett. B **216** (1989) 392

[Br76] F.W.Brasse, et.al., Nucl. Phys. **B110** (1976) 413

[Ca78] R.N.Cahn and F.J.Gilman, Phys. Rev. D **17** (1978) 1313

[Dm89] V.Dmitrosinovich, private communication

[Do88] T.W.Donnelly, et.al. Phys. Rev. C **37** (1988) 2320

[Do89] T.W.Donnelly, et.al. "Isospin Dependences in Parity Violating Electron Scattering", MIT/LNS Preprint, to be published.

[Du89] J.Dubach, private communication, to be published.

[Fr67] R. Frosch, et.al. Phys. Rev. **160** (1967) 874

[Fr68] R. Frosch, et.al. Nucl. Phys. **A110** (1968) 657

[Ga71] S.Galster, et.al. Nucl Phys **B32** (1971) 221

[Ge89] Howard Georgi, et.al. Phys. Rev. Lett. **62** (1989) 2789

[Ha89] W.C. Haxton, et.al. Phys. Rev. Lett. **63** (1989) 949

[Ja87] R.L.Jaffe and C.L.Korpa, Comments in Nuclear and Particle Physics **17** (1987) 163

[Jo89] D.Joyce, CLAS-NOTE-89-004, Unpublished

[Ka88] D.B.Kaplan and A.Manohar, Nucl. Phys. **B310** (1988) 527

[Kl88] E.Klemt, et.al. Zeit. Phys. C **37** (1988) 179

[Ly87] J.Lykken, Phys. Lett B **193** (1987) 123

[Ly87a] J.Lykken, LANL Reports LA-UR-87-1051 and LA-UR-87-1282

[Mc89] R.D.McKeown, Phys. Lett. B **219** (1989) 140. Note that in Eqn.7 the factor in front of the axial term should be $(E + E')/2M_N$, instead of $(E + E')/M_N$.

[Me89] B.Mecking, et.al. in CEBAF Preconceptual Design Report on Experimental Equipment (December 1988)

[Mi88] R.Milner (spokesperson), MIT/Bates proposal 88-25

[Mi88a] R.Michaels, Ph.D. Thesis, Yale University (1988) Unpublished

[No89] M.A.Nowak, et.al. Phys. Lett. B **217** (1989) 157

[Po87] S.J. Pollock, Ph.D. Thesis, Stanford University (1987) Unpublished

[Re74] E.Reya and K.Schlichter, Phys. Rev. D **10** (1974) 952

[Se79] B.D.Serot, Nucl. Phys. **A322** (1979) 408

[Wa77] J.D.Walecka, Nucl. Phys. **A285** (1977) 349

[Wa89] R.C.Walker, et.al. Phys. Lett. B **224** (1989) 353

[We72] S.Weinberg, Phys. Rev. D **5** (1972) 1412

[Yu86] V.Yuan, et.al. Phys. Rev. Lett. **57** (1986) 1680